(REFEREED RESEARCH)

STUDY OF THE FABRIC PERMEABILITY EFFECT ON PARACHUTE DROPPING BASED ON ALE METHOD

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ABSTRACT

The fabric permeability has great effect on parachute opening and deceleration characteristics, therefore that property would be fully considered in parachute design. However whether the fabric permeability is reasonable needs a series of airdrop experiments to confirm. In this paper, the C9 parachute was taken as the research object, and then the finite element method based on Arbitrary Lagrange Euler (ALE) algorithm was used to simulate the actual airdropping process, and the Ergun equation to simulate the dynamic permeability. Through the explicit calculation, the deceleration characteristics such as dropping velocity, acceleration, and rich flow field information were obtained. Four models with different fabric permeability were calculated by the above method in this paper. According to the results analysis, it was found that the parachute opening is related with the size of bulb shape, and the bulb shape formed in inflating process is closely related with the fabric permeability, which could be used to guide the parachute design.

Keywords: Porous textiles, macro permeability, materials mechanics, polyamide, numerical simulation.

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1. INTRODUCTION

Permeability is a physical property of the fabric, and the fabric permeability is an important physical property of parachute. The fabric permeability has great effect on canopy stability, dynamic load, opening performance, etc. There exit different requirements on different opening phases. In inflating phase, increasing the permeability is necessary to decreases the opening load and impact on parachutists or goods, while decreasing the permeability is used to ensure the landing velocity and safety in steady dropping phase. Therefore, selecting the reasonable fabric is very important in parachute design.

Although the principle of parachute opening is simple, the whole process is a typical fluid structure interaction and the pressure difference changing between inside and outside of the canopy follows the canopy shape changing at any time, which is a complex transient and nonlinear process. In addition, the fabric permeability is positively correlated with the pressure difference between inside and outside of canopy. It is difficult to obtain the relationship between the fabric permeability and the changing shape by airdrop experiments or wind tunnel experiments. At present, the selection of fabric material in parachute design mainly depends on experience, and verified by many airdrop experiments.

With the development of numerical algorithms and upgrading of computer hardware, the numerical simulation is becoming an important research means due to its advantages of economy, flexibility and repeatability. From the 1980's, the researchers began to use the Fluid Structure Interaction (FSI) method to study the parachute inflation process. The representative studies are as following. Purvis achieved the two-dimensional coupling calculation by simplified the canopy structure and fluid field model [1]. Stein, Benney and Steeves proposed the CFD/MSD coupling model, which ignored the impact of fabric characteristics [2]. Kim and Peskin used Immersed Boundary (IB) method to simulate the three-dimensional parachute in finite mass situation, but there are no results such as overload, structure stress [3]. These research works ignored the fabric permeability generally. On the other hand, the researches on the air permeability of fabric began at the end of the 19th century and mainly at mesoscopic level [4-7], and the small-scale grid is utilized to discretize spatial domain among the fabric fibers and the flow simulation is calculated among the fiber gaps. But the parachute aerodynamic performance analysis is macro issue, and the flow around parachute contains flow separation, vortex formation and shedding. If the fabric and flow field is discretized by small-scale grid, the grid number will reach hundreds of millions which is difficult to achieve in current computing capacity. However in recent years, the researches on fabric permeability based on FSI method are just catching up. In 2006, Aquelet used the Euler Lagrange Coupling (ELC) method to simulate the channel tests of polyamide MIL-c-7020 type Ⅲ the first time, and the results were compared with the experiments [8]. In 2009, Jia applied the same method to verify the results of Aquelet's work [9], but the method couldn't be used for simulating the parachute dropping.

In this paper, four finite element models with different fabric permeability were established, and the dropping processes of those models were calculated by Arbitrary Lagrange Euler method. The rich information of flow field and deceleration characteristics was obtained. According to the results, the relationship between the permeability and the fabric deformation were obtained.

2. MATERIALS AND METHODS

2.1 Numerical methods

The finite element model is different form the other models used in most woven fabric studies [10-13]. That model can not only reflect the mechanical properties also can realize the dynamic simulation. In this paper, both the permeable fabric and flow field were described by using the Lagrangian mesh, the mass conservation is satisfied naturally. Only the momentum conservation equation needs to be discrete:

$$\rho\frac{\mathrm{D}\boldsymbol{v}}{\mathrm{D}t}=\nabla\cdot\boldsymbol{\sigma}+\rho\boldsymbol{b} \tag{1}$$

Where, $\boldsymbol{v}$ is the velocity vector, $\boldsymbol{\sigma}$ is the stress vector, $\boldsymbol{b}$ is the body force vector, ρ is the density.

The spatial discretization scheme of the momentum equation can be obtain according to the virtual work principle.

Where, B_{Ij} is the geometry matrix represented by index form, σ_{ji} is stress, $\bar{t}_i$ is the external force, N_I and N_J are shape functions, $\dot{v}_{Ji}$ is the acceleration, $\boldsymbol{f}^{\mathrm{int}}$ is the internal force matrix $\boldsymbol{f}^{\mathrm{ext}}$ is the external force matrix, $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{a}$ is the acceleration matrix.

Except the spatial discretization, that the parachute opening process with large displacement and deformation should be discretized in time (Figure 1). Here, the central difference scheme, the most widely used in nonlinear dynamics, was used to discretize the semi discrete equation.

At each time step, the movements and deformation of finite elements used to described fabric or fluid are calculated. These Lagrange elements can accurately describe the nodes displacement, but the fact, the fluid material couldn't bear the shear stress and tension, would cause the serious element distortion or negative volume. Therefore, the elements used to describe the fluid must be restructured after each Lagrange calculation step, and the information of original elements should be transport to the updated elements (Figure 2). The specific process could be divided into three steps, which was described in detail in the authors' previous works [14].

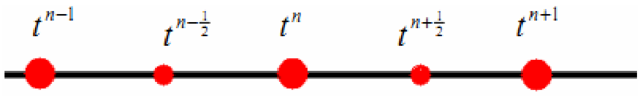


Figure 1. The time axis

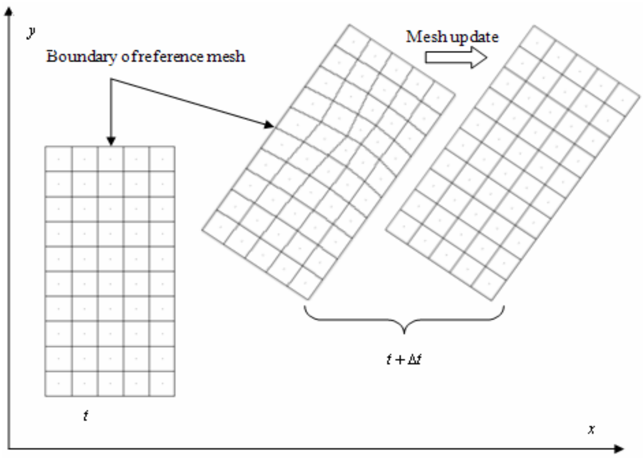


Figure 2. the principle of ALE

$$\underbrace{\int_{\Omega} B_{Ij}\sigma_{ji}\mathrm{d}\Omega}_{f_{Ii}^{\mathrm{int}}} - \underbrace{\left(\int_{\Omega} N_I\rho b_i\mathrm{d}\Omega + \int_{\Gamma_{t_i}} N_I\bar{t}_i\mathrm{d}\Gamma\right)}_{f_{Ii}^{\mathrm{ext}}} + \underbrace{\delta_{ij}\int_{\Omega} N_I N_J\rho\mathrm{d}\Omega}_{M_{ijIJ}}\,\dot{v}_{Ji} = \boldsymbol{f}^{\mathrm{int}} - \boldsymbol{f}^{\mathrm{ext}} + \boldsymbol{M}\boldsymbol{a} = 0 \tag{2}$$

$$\boldsymbol{v}^{n+\frac{1}{2}}=\boldsymbol{v}^{n-\frac{1}{2}}+\Delta t^{n}\boldsymbol{M}^{-1}(\boldsymbol{f}^{\mathrm{ext}}(\boldsymbol{d}^{n},t^{n})-\boldsymbol{f}^{\mathrm{int}}(\boldsymbol{d}^{n},t^{n}))=\boldsymbol{v}^{n-\frac{1}{2}}+\Delta t^{n}\boldsymbol{M}^{-1}\boldsymbol{f}^{n} \tag{3}$$

2.2 Numerical model

According to the geometry parameters of C9 parachute described in relevant references [15], the finite element model in folded state was established firstly. It is different with the original canopy structure that the whole canopy was divided into upper and lower parts, and the distance from top vent to the dividing line is about 1m (Figure 3). The canopy and lines are meshed by three nodes triangular elements (14,000) and bar elements (1,932). The eight nodes hexahedral elements (921,600) are used to mesh the flow field. The canopy and fluid domain interpenetrate. The initial velocity (20.7 m/s) and the gravity acceleration (9.8 m/s^2) are given to the payload (100 kg).

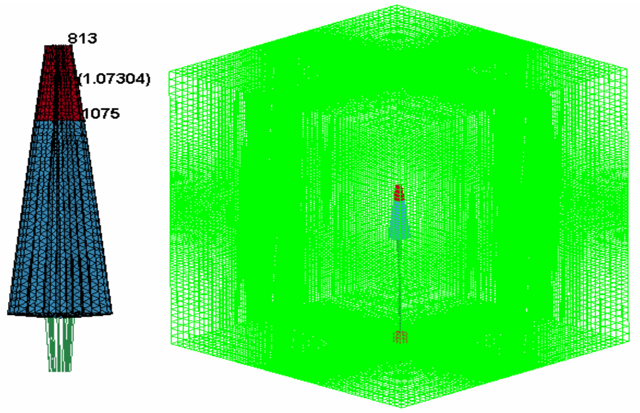


Figure 3. finite element model of canopy and flow field

2.3 Numerical description of Permeability

For the parachute opening process, the fabric permeability described by static Darcy's law is inappropriate. Therefore the Ergun equation developed from Forchheimer equation [16] was used to describe the relationship between pressure difference and fluid velocity.

$$\Delta p = [a(\mu,\varepsilon)\cdot \boldsymbol{v}\cdot \boldsymbol{n} + b(\rho,\varepsilon)\cdot(\boldsymbol{v}\cdot\boldsymbol{n})^2]\cdot e \qquad (4)$$

Where, $a(\mu,\varepsilon)$ is the reciprocal permeability of the porous shell coefficient; $b(\rho,\varepsilon)$ is the inertia coefficient; e is the fabric thickness; $\boldsymbol{n}$ is the normal vector; $\boldsymbol{v}$ is the fluid velocity vector through the fabric.

In equation (4), the coefficients a and b are fitting constants from the experiments results. The vector $\boldsymbol{v}$ is relative velocity between the fluid and fabric movements, $\boldsymbol{v} = \boldsymbol{v}_{\text{fluid}} - \boldsymbol{v}_{\text{fabric}}$, which could be obtained by calculation. Then the coupling force $\boldsymbol{f}_{\text{couple}}$ derived from the equation (4) is applied to both the fluid and fabric in opposite directions to satisfy force equilibrium, and the coupling force $\boldsymbol{f}_{\text{couple}}$ are taken as a part of external force $\boldsymbol{f}^{\text{ext}}$ in equation (2) and equation (3).

2.4 Permeable materials

Here, the C9 parachute used the polyamide K59225 and polyamide K58326 in different canopy parts, and four models with different fabric material were established and divided into two groups in this paper (Table 1).

In order to obtain those permeability coefficients, the permeability experiments were carried out by the YG461D tester followed the Chinese national standard GB/T5453-1997 (Figure 4).

The pressure drop is obtained according to the difference of atmospheric pressure P_0 and front chamber pressure P_1. The unit flow, which can be viewed as relative velocity, is obtained according to the nozzle diameter, the front and the rear chamber pressure. The polyamide K29225 and polyamide K58326 are tested, and the experimental data are fitted according to the equation (4) by Origin 8.0. The fabric permeability coefficients are shown in Table 2. It can be found that the polyamide K59225 has higher permeability than the polyamide K58326.

Table 1. Definition of four models

	upper canopy part	lower canopy part	
Model A	K59225	K59225	the first group
Model B	K58326	K58326	
Model C	K58326	K59225	the second group
Model D	K59225	K58326	

Table 2. permeability coefficients of polyamide K29225 and polyamide K58326

	a (kg/m^3·s)	b (kg/m^4)	e (m)
K59225	1.05E+6	4.9E+5	1E-4
K58326	1.1E+6	1E+6	1E-4

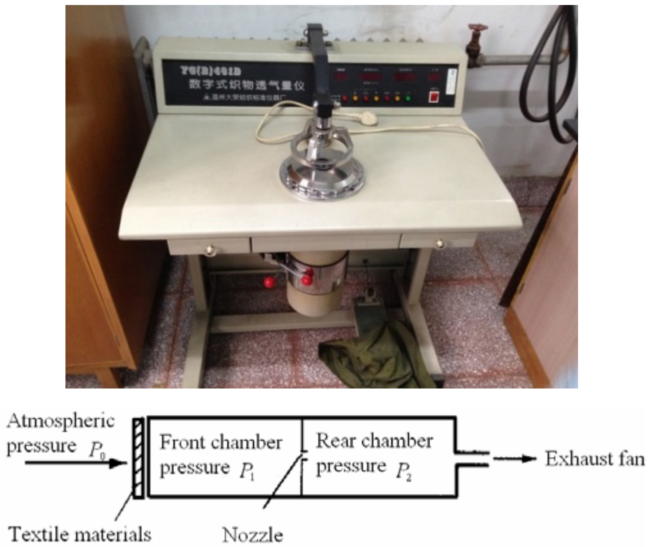


Figure 4. Permeability tester (left: YG461D tester; right: principle)

3. RESULTS AND COMPARIOSN

3.1 Comparison and analysis of the first group

Figure 5 shows the canopy size change (the projected diameter and vent diameter), while Figure 6-7 show the acceleration and velocity change respectively.

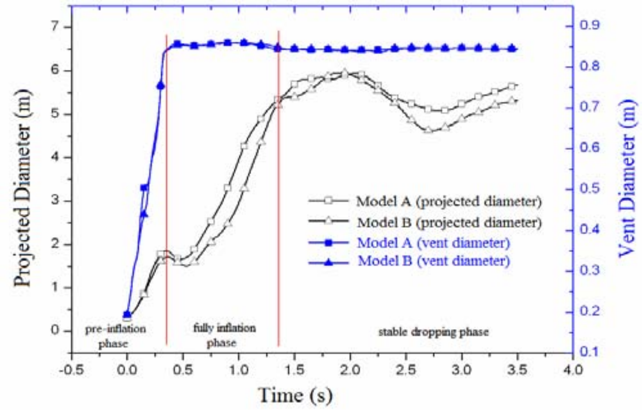


Figure 5. The comparison of projected diameter and vent diameter (Model A and Model B)

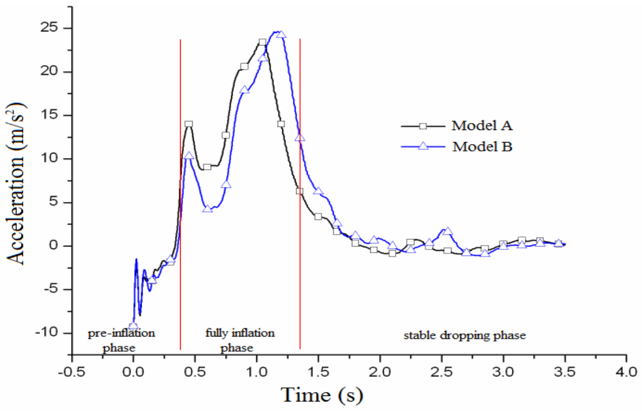


Figure 6. the comparison of acceleration (Model A and Model B)

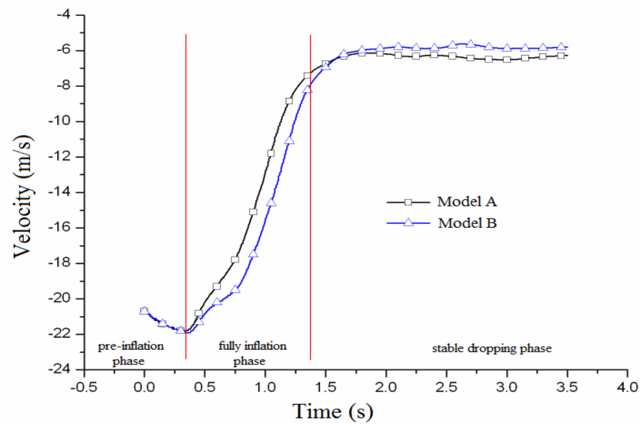


Figure 7. the comparison of velocity (Model A and Model B)

The parachute inflation process could be divided into three phases, the pre-inflation phase (0-0.37s), the fully inflation phase (0.37s-1.39s), and the stable dropping phase (after 1.39s).

Pre-inflation phase (0-0.37s)

The fabric permeability had little effect on parachute inflating, and both the canopy deformations were basically the same.

Fully inflation phase (0.37s-1.39s)

The vents of two models were completely opened, which indicated the beginning of the fully inflation phase (0.37s). The bottom inlets began to shrink inward temporarily, and the canopies formed a bulb shape (Figure 8). The Model B shrank more strongly than Mode A, and the bulb shape was more obvious (Figure 9). The Model B with smaller inlet could reduce the air sending into the canopy, and then reduce the dynamic load and the first peak acceleration (Figure 6). The smaller inlet could delay the canopy opening (Figure 5 and Figure 7). However, with the canopy inflating and the drag area increasing, the effect of fabric permeability on parachute opening was more obvious. The expanding of Model B with less permeability was accelerated, and nearly formed a fully inflated shape at the same time with Model A (at 1.39s when the projected diameter was 5.4 m). At the same time, the maximum overload of the Model B was greater than that of the Model A.

Stable dropping phase (after 1.39s)

The projected diameter change of the Model B was greater than that of Model A obviously (Figure 5), because the parachute breathing phenomenon occur on Model B with lower permeability was more strongly than Model A. In addition, the former's stable dropping velocity of 5.8 m/s was less than the latter of 6.28 m/s.

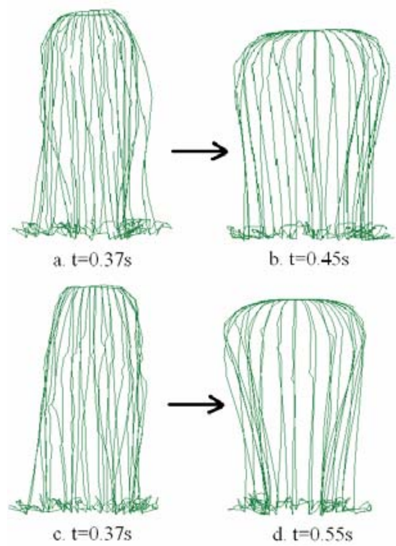


Figure 8. the formation of bulb shape (up: Model A; down: Model B)

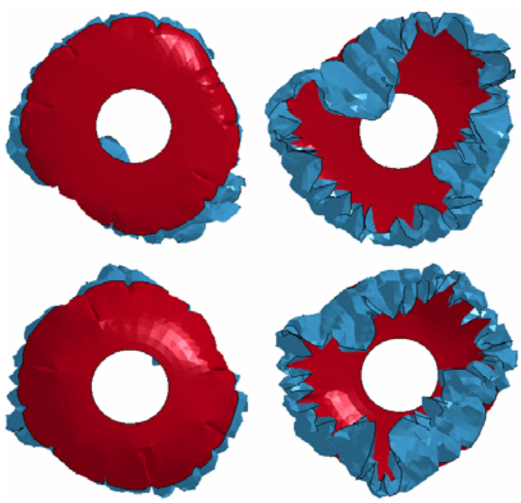
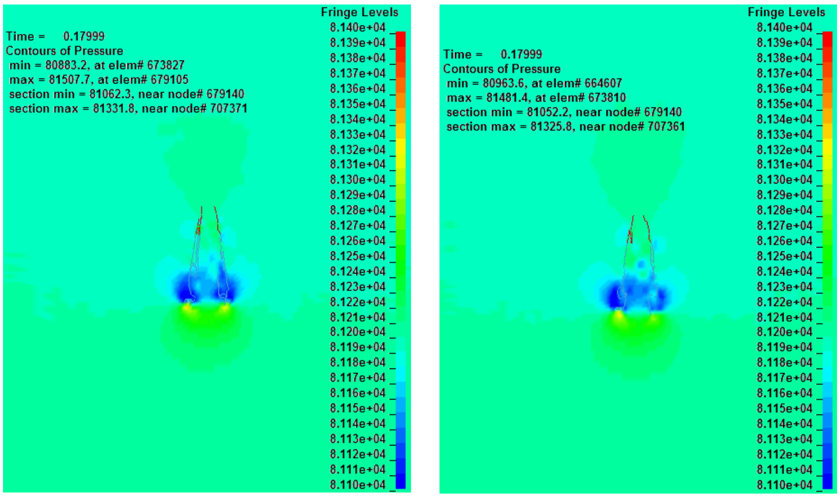


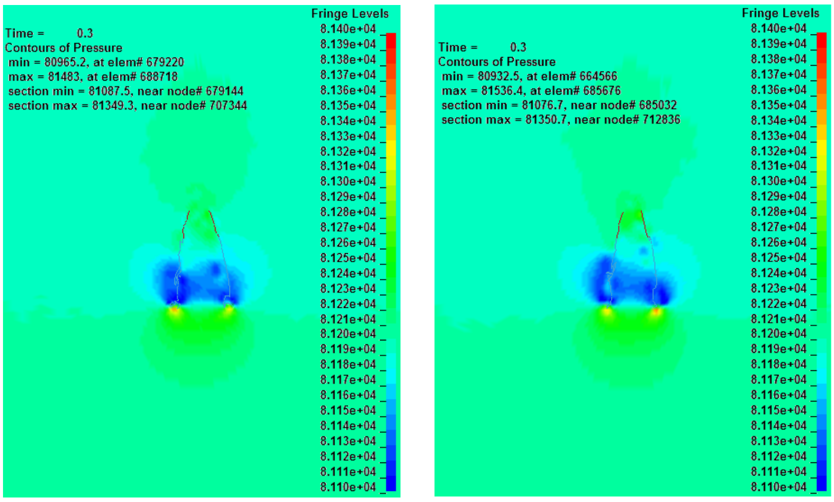
Figure 9. The comparison of bulb shape (up: Model A at 0.45s; down: Model B at 0.55s)

Figure 10 shows the pressure contours of Model A and Model B to explain the interaction between the canopy and the flow field.

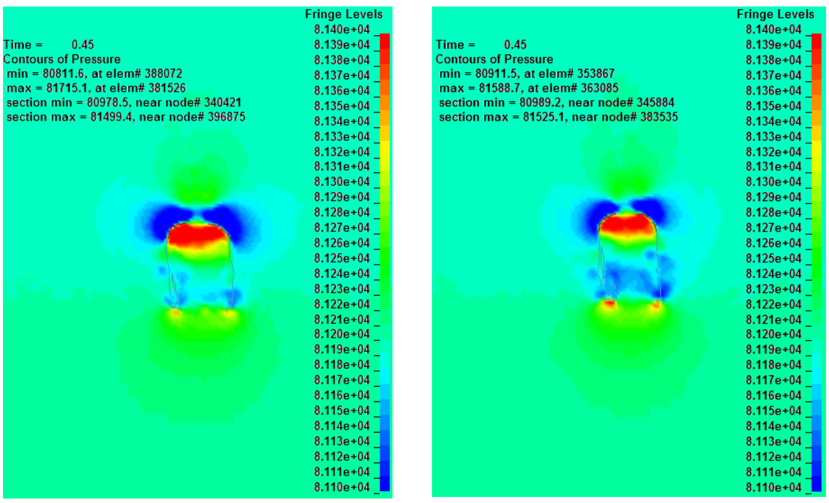
a. t=0.18s



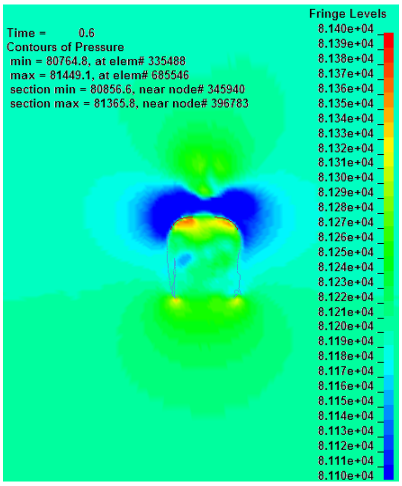
b. t=0.3s

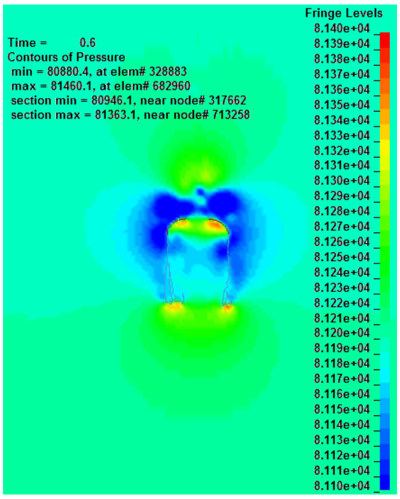


c. t=0.45s

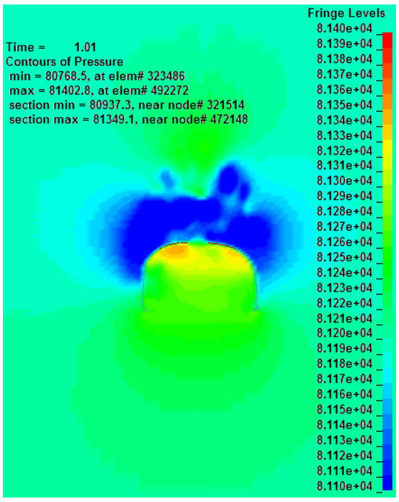


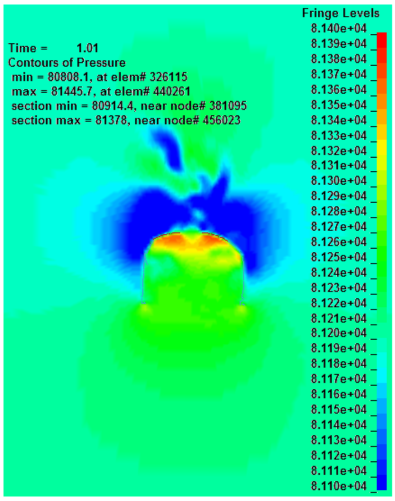
d. t=0.6s



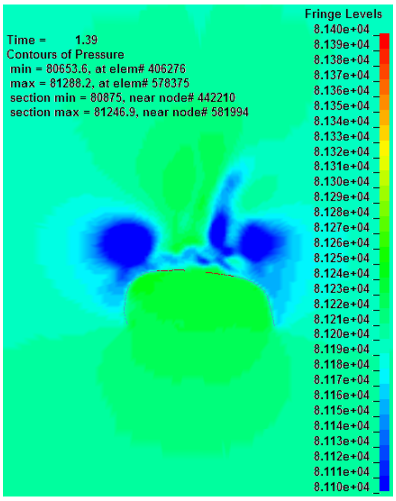


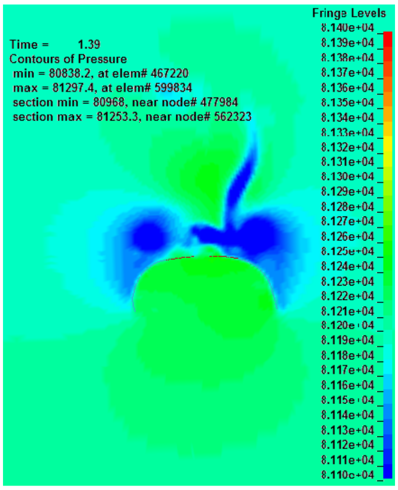
e. t=1.01s





f. t=1.39s





Model A Model B

Figure 10. The comparison of pressure contours (Model A and Model B)

It could be found that the fabric permeability had little effect on parachute opening in pre-inflation phase (Figure 10a-b). The vents hadn't been opened, and high pressure areas were mainly concentrated at the canopy bottom.

With the vent opening rapidly, the Model B's internal air pressure was higher than Model A's due to the lower fabric permeability. It could be found that the flow field near the lower part of Model B had a certain pressure difference

(Figure 10c), which caused the bottom relaxed canopy continued to shrink inward and the projected diameter continue to reduce (Figure 5). Until the 0.55s, the Model B finally formed a more obvious bulb shape (Figure 8) and began to expand from top canopy to bottom. While the Model A had formed a bulb shape at 0.45s, and then began to expand. But the lower fabric permeability caused the Model B's expanding velocity was faster than Model A and two models were fully inflated almost at the same time (Figure 10d-f).

3.2 Comparison and analysis of the second group

Figure 11-13 show the size, acceleration and velocity change respectively.

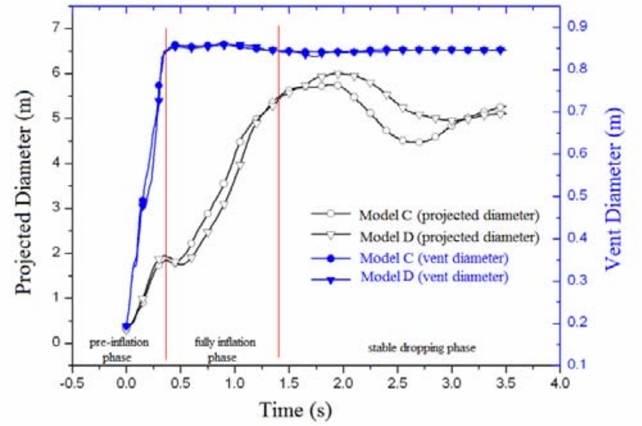


Figure 11. the comparison of projected diameter and vent diameter (Model C and Model D)

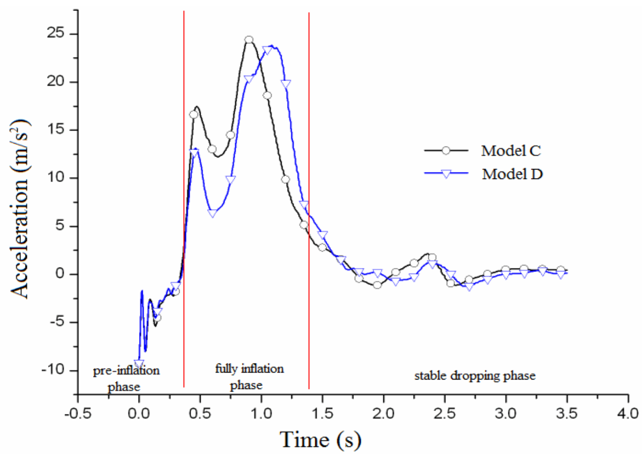


Figure 12. the comparison of acceleration (Model C and Model D)

The opening processes also could be divided into three phases.

Pre-inflation phase (0-0.37s)

The fabric permeability had little effect on parachute inflating, and both the canopy deformations were basically same with Model A and B.

Fully inflation phase (0.37s-1.39s)

In the process of forming the bulb shape, the flow field results shown that the internal pressure of the Model D was always lower than that of the Model C on the upper canopy part and there existed pressure difference on the lower canopy part (Figure 14). Because the fabric permeability of Model D's upper part (polyamide K59225) was higher than the lower canopy part (polyamide K58326), while the Model C was just the opposite. Under the function of the pressure difference, the canopy bottom of Model D continued to shrink inward. But with the expanding of the bottom canopy, the expanding velocity of Model D was gradually faster than that of Model C (Figure 11). It was worth noting that the Model D's two acceleration peaks were smaller than the Model C's for the upper canopy with higher fabric permeability (Figure 12).

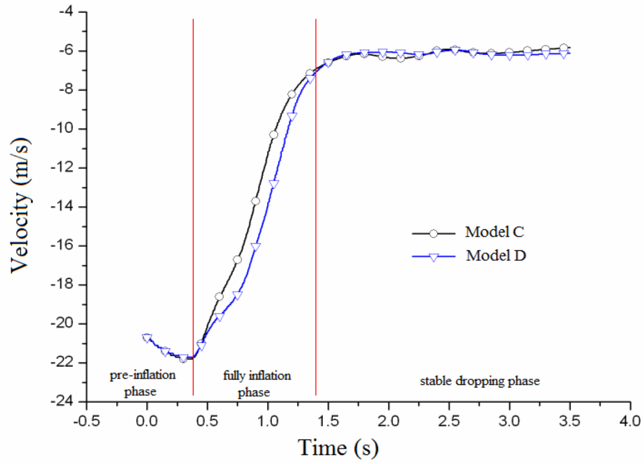


Figure 13. the comparison of velocity (Model C and Model D)

Stable dropping phase (after 1.39s)

The Model D's stable dropping velocity was 6.1 m/s and the Model C's was 5.9 m/s, which were almost between the Model A's and Model B's (Figure 13).

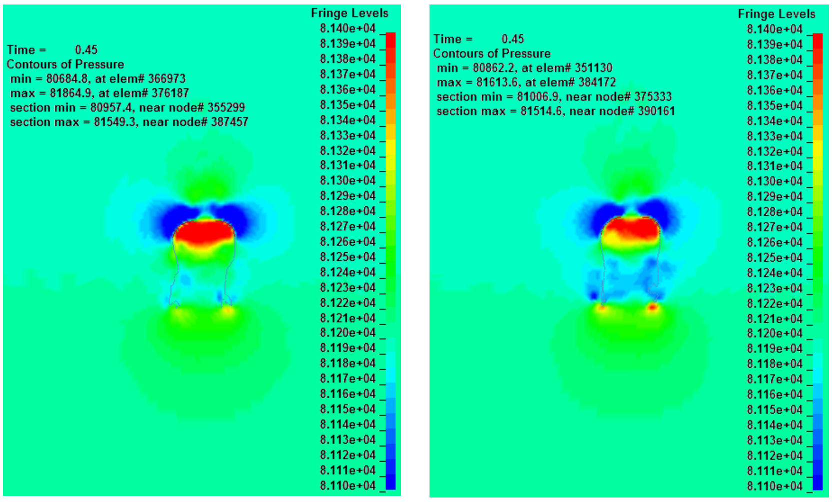
4. CONCLUSIONS

In this paper, the numerical method was used to study effect of fabric permeability on parachute opening. The conclusions are following.

a. If the parachutes are same in structure, the high permeability fabric can decrease the overload peak but increase the stable dropping velocity (Model A), while the low permeability fabric is just the opposite (Model B).

b. The bulb shape formed at the end of pre-inflation phase is closely related with the lower canopy's material. The lower the fabric permeability, the more strongly bottom canopy and the more obvious the bulb shape (Model B and Model D). The bottom shrinking can delay the canopy expanding, but with the canopy bottom expanding, the low permeability can accelerate the canopy expanding.

c. If the parachute uses the high permeability fabric on the upper canopy and the low permeability fabric on the lower canopy (Model D), the parachute can effectively avoid the overload impact and reduce the landing velocity. That is consistent with the design principles used in actual engineering.



Model C Model D

Figure 14. the comparison of pressure contours at 0.45 s (Model C and Model D)

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